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ScienceDirect
Procedia Engineering 62 (2013) 829 – 836
Procedia Engineering
www.elsevier.com/locate/procedia

The 9th Asia-Oceania Symposium on Fire Science and Technology

THIEF model evaluation for cables used in nuclear plants in Japan

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Abstract

Many nuclear power plants in the U.S. and elsewhere are transitioning from a prescriptive to a risk-informed performance-based fire protection program. The acceptance of a proposed performance-based fire protection program is partly based on the results of a probabilistic risk assessment (PRA), which quantifies the likelihood of core damage and harmful radiological release in the event of a fire. The fire PRA relies on engineering analyses to determine the effect of fires on safety-related equipment and components, such as electrical cables critical for safe plant shutdown. The report of the CAROLFIRE research program published in 2008 provides thermal and electrical performance data for a broad range of cable types used in U.S. nuclear power plants. The report also describes the thermally-induced electrical failure (THIEF) model, which estimates the temperature response of a cable for a specified thermal exposure. The purpose of the research described in this paper was to obtain thermal and electrical performance data and to evaluate the predictive capability of the THIEF model for some cables that are used in nuclear plants in Japan. Two types of cables were tested, designated as CCV and PSHV. The average fire-induced electrical failure temperature under the jacket of the CCV cable was approximately 400 °C. The average failure temperature of the PSHV cable was approximately 370 °C. Both Japanese cables therefore performed like the thermoset cables in the CAROLFIRE tests. The THIEF model predictions are in remarkably good agreement with the measured cable temperatures for the tests in which electrical failure was observed. However, the model overestimates the cable temperature at the end of the tests in which failure was not observed.

Selection and peer-review under responsibility of the Asian-Oceania Association of Fire Science and Technology

Keywords: Electrical cables; Nuclear plants; Penlight; Performance-based fire protection; THIEF model

Nomenclature

c	specific heat capacity (kJ/kg·K)	*Greek symbols*	
h	convection coefficient (kW/m^2·K)	ε	surface emissivity
k	thermal conductivity (W/m·K)	ρ	density (kg/m^3)
$\dot{q}''$	heat flux (kW/m^2)	σ	Boltzmann constant (5.67·10^{-11} kW/m^2·K^4)
r	radial coordinate (m)	*Subscripts*	
t	time (s)	g	gauge
R	cable radius (m)	net	net
T	temperature (°C or K)	s	shroud

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Selection and peer-review under responsibility of the Asian-Oceania Association of Fire Science and Technology
doi:10.1016/j.proeng.2013.08.132

1. Introduction

An increasing number of nuclear power plants in the U.S. and elsewhere are transitioning from a prescriptive to a risk-informed performance-based fire protection program. The acceptance of a proposed performance-based fire protection program depends on the ability of the plant operator to provide reasonable assurance that a fire will not result in damage to the fuel core and harmful radiological release. This assurance is partly based on the results of a probabilistic risk assessment (PRA), which quantifies the likelihood of core damage and large radiological release in the event of a fire. The fire PRA in turn is based on engineering analyses to determine the effect of fires in each area on structures, equipment and components. Electrical cables that are critical for the safe shutdown of the plant are the primary targets that need to be considered in these analyses.

In 2008 the U.S. Nuclear Regulatory Commission published the results of the CAROLFIRE research program. The first two volumes of the CAROLFIRE report provide thermal and electrical performance data for a broad range of electrical cable types used in U.S. nuclear power plants [1, 2]. CAROLFIRE testing comprised 78 small-scale and 18 intermediate-scale open burn tests. The small-scale tests involved exposure of one or several lengths of cable to radiant heating in a cylindrical exposure chamber called Penlight. A broad range of thermoplastic and thermoset insulated cables were tested. All Penlight tests measured the cable thermal response using thermocouples embedded within the target cables, and cable electrical performance was monitored using an insulation resistance measuring system (IRMS). The temperature under the jacket of thermoplastic cables at electrical failure (development of short between two conductors or between a conductor and ground) ranged from approximately 200-250 °C. Failure temperatures for thermoset cables ranged from approximately 400-450 °C.

Volume 3 of the CAROLFIRE report documents the thermally-induced electrical failure (THIEF) model, which was developed and validated based on the aforementioned Penlight test data [3]. The THIEF model takes, as input, an estimate of the radiative and convective heat flux to a cable during a fire and predicts, as output, the temperature response of the cable. The time to electrical failure is then based on an assumed failure threshold temperature characteristic of the cable of interest.

The purpose of the research described in this paper was to obtain thermal and electrical performance data for cables that are used in nuclear plants in Japan and to evaluate the predictive capability of the THIEF model for these cables. Two types of cables, designated as "CCV" and "PSHV", were tested in a Penlight apparatus at Southwest Research Institute® (SwRI®) in San Antonio, Texas. The experimental setup and heat flux calibrations are described in detail in the next section, as well as the cables that were tested and the results that were obtained. The THIEF model calculations for the two cables are discussed in the next section. Conclusions and recommendations for future work are presented at the end of the paper.

2. Experimental

2.1. Test setup

An apparatus was constructed at SwRI similar to the Penlight chamber used in the small-scale CAROLFIRE tests at Sandia National Laboratories (SNL) in Albuquerque, New Mexico. The apparatus consists of a cylindrical ring of rod-shaped 0.61-m long quartz heating lamps, each held in a water-cooled aluminum fixture with a reflector to direct the heat toward the center of the lamp array. An Inconel cylindrical shroud, approximately 0.51 m in diameter and 0.81 m long, is installed within the array of heating lamps. The shroud is painted with high-temperature flat black paint. The quartz lamps are used to heat the shroud to a desired (and controlled) temperature. The shroud in turn acts as a grey-body radiator heating any target object located within it. Twenty-eight grounded junction Inconel sheathed thermocouples (1 mm diameter) are installed to monitor the temperature distribution along the length and the perimeter of the shroud. A separate centrally located thermocouple provides the input signal for the power controller.

In addition, a system was built at SwRI to measure the electrical insulation resistance between pairs of conductors and between each conductor and ground during exposure in the Penlight chamber. The system was based on the insulation resistance measurement system (IRMS) at SNL described in Appendix B of Volume 1 of the CAROLEFIRE report [1]. The IRMS at SwRI is capable of providing electrical resistance data for cables with up to eight conductors. For a cable with eight conductors, a complete set of resistance measurements can be obtained in less than 50 seconds. For a three-conductor cable the fastest scan rate reduces to less than 10 seconds. A functional check showed than resistances between 1 and 20 kΩ measured with the IRMS are better than 1% of the actual values.

2.2. Heat flux calibration

A series of calibrations were performed to establish a relationship between the shroud temperature and the incident heat flux in the Penlight apparatus at SwRI. The calibrations involved measuring the heat flux to a 13-mm diameter Schmidt-Boelter heat flux gauge at different shroud temperatures. The gauge was mounted in a 13-mm calcium-silicate dummy board backed by 25-mm thick ceramic fiber blanket. The gauge was located at the center of the shroud and faced the upper half of the shroud. The dummy board was mounted on a ladder tray to closely simulate the thermal environment that a cable specimen is exposed to in a test. The results of the heat flux measurements with the shroud closed off at one end are given in Table 1. The following empirical relationship was established to determine the heat flux as a function of the shroud temperature:

$$\dot{q}''_{net} = \varepsilon_s \sigma T_s^4 - \sigma T_g^4 + h\left(T_s - T_g\right) \tag{1}$$

The best fit was obtained for $\varepsilon_s = 0.9$ and $h = 0.008$ kW/m^2·K and is shown in Fig. 1 below. The resulting calculated heat fluxes at the control thermocouple temperatures at which the flux calibrations were performed are included in Table 1.

Table 1. Measured and calculated heat flux as a function of Penlight shroud temperature

Control TC temperature (°C)	Measured heat flux (kW/m^2)	Calculated heat flux (kW/m^2)
434	14.5	14.7
532	24	24
616	35	35
687	49	47
770	65	65
839	83	83
886	98	98

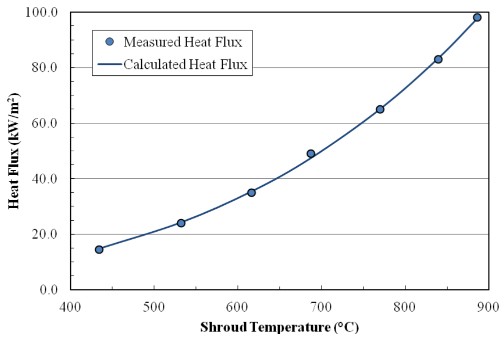

Fig. 1. Best fit of gauge heat flux as a function of Penlight shroud control thermocouple temperature.

To determine how the heat flux varies along the cable specimens, the heat flux profile was measured at control thermocouple temperatures of 470 °C and 665 °C. The results are given in Table 2. The heat flux is within ±0.5 kW/m^2 over the central 0.25-m section of the shroud at a control thermocouple temperature of 470 °C, and within ±1.3 kW/m^2 at 665 °C. The average heat flux over the five interior locations is 15.1 kW/m^2 and 37.9 kW/m^2 for the two shroud temperatures, respectively. These values are slightly higher than the heat fluxes at these shroud temperatures calculated by SNL, *i.e.* 14.1 kW/m^2 and 35.8 kW/m^2 respectively (see page 30 of Reference [1]). This discrepancy might, for example, be due to heat flux measurement errors or a lower than actual shroud emissivity in the SNL calculations. Finally, the heat flux calibrations showed that the shroud temperature rises from ambient to 470 °C in approximately 50 s and to 665 °C in about 90 s.

Table 2. Heat flux profile at shroud control thermocouple temperatures of 470 °C and 665 °C

Distance from open end (m)	Heat flux for T_s = 470 °C (kW/m^2)	Heat flux for T_s = 665 °C (kW/m^2)
0.025	7.1	18.7
0.152	12.4	31.2
0.279	16.0	39.3
0.406	17.0	41.9
0.533	16.4	41.0
0.660	13.6	36.0
0.787	11.2	31.1

2.3. Test specimens

Table 3 provides some important characteristics of the two cables that were tested. In each test, two specimens of the cable were exposed to the radiant heat from the shroud of the Penlight apparatus. One cable specimen was instrumented with five thermocouples embedded into the cable (two directly under the jacket and three at various depths below the jacket). The other cable specimen was connected to the IRMS. The two cable specimens were fixed with clamps to the rungs of a standard 300-mm wide ladder-backed pre-galvanized steel cable tray, as shown in Fig. 2. Care was taken to ensure that none of the cable thermocouples were shielded by a rung. The cable tray was identical to that used in the CAROLFIRE program (see page 31 in reference [2] for a detailed description) except that it was 3 m instead of 3.6 m long. The exposed part of the cable specimens was positioned at 38 mm on either side of the center of the cable tray resulting in a spacing of 76 mm between the two cable specimens. Prior to the test the cable tray was routed through the Penlight shroud and positioned horizontally so that TC 2 was at equal distances from both ends of the shroud and positioned vertically so that the top of the rungs was approximately 3 mm below the horizontal centerline of the Penlight shroud (see Fig. 2).

Table 3. Characteristics of the two cables that were tested in the Penlight apparatus

Designation	Insulation/Jacket	Diameter (mm)	Jacket thickness (mm)	Mass per length (kg/m)	Copper mass fraction
CCV	XLPE/PVC	14.4	1.6	0.29	0.50
PSHV	EPR/PVC	15.8	1.7	0.44	0.44

2.4. Results

A total of nine Penlight tests were conducted; a preliminary test on the CCV cable and four additional tests on each of the two types of cable. Baseline data were collected for a period of two minutes at the start of a test. Power was then turned on to heat the Penlight apparatus to the preset shroud temperature. A PID controller was used to minimize the heating time without excessive overshoot of the target shroud temperature. All tests except the preliminary CCV test were terminated after one hour of exposure, or sooner if electrical failure of all conductors was observed.

The primary purpose of the preliminary CCV test was to identify problems or issues that needed to be addressed before the actual Penlight tests were conducted. In this test the shroud temperature was initially set at 300 °C. After 45 and 60 minutes the shroud temperature was increased to 340 °C and 400 °C, respectively. Finally, after 75 minutes the shroud temperature was increased to 470 °C and all cables started to fail at approximately 85 minutes (initially conductor to conductor and on the next scan, 45 s later, conductor to ground). Electrical failure coincided with ignition of the cable. The cable specimen connected to the IRMS ignited first. The maximum cable temperature immediately prior to ignition was approximately 382 °C.

In the next three tests on the CCV cable specimens, electrical failure was not observed during 60 minutes of exposure. The shroud temperature in these three tests was 380 °C, 410 °C, and 440 °C, respectively. The shroud temperature during the final CCV test was 470 °C. In this test the cable started failing between 965 and 1025 seconds into the test (Conductor 1 to Ground short). Ignition was observed shortly thereafter. The maximum cable temperature immediately prior to ignition was approximately 442 °C as shown in Fig. 3.

In the first PSHV test the cable failed between 952 and 956 seconds, *i.e.* after nearly 14 minutes of exposure to the radiant heat flux from the Penlight shroud heated at 470 °C. The highest cable thermocouple temperature at that time was 368 °C. The first electrical failure occurred between Conductor 1 and Ground. Consistent with the values used in the CAROLFIRE program, the failure threshold was set at 1,000 Ω while the insulation resistance of undamaged cable was assigned a value of 300 kΩ (e.g., see pages 32 and B-5 in Reference [1], respectively).

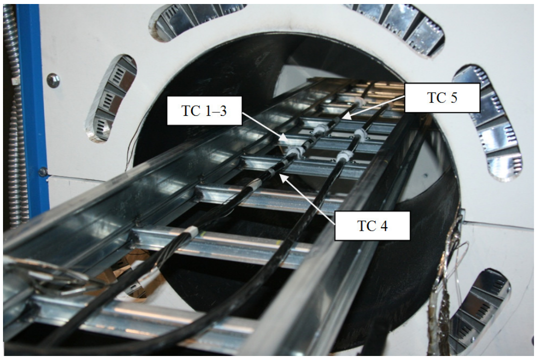

Fig. 2. Tray with cable specimens positioned inside the Penlight chamber prior to testing.

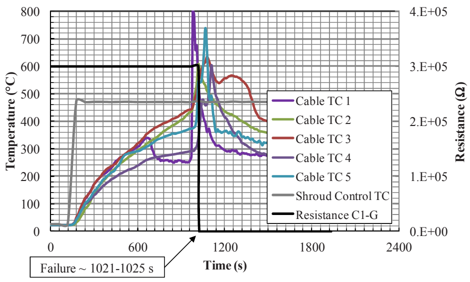

Fig. 3. Temperature and electrical resistance data obtained in the final CCV test.

The shroud temperature in the second PSHV test was 440 °C. Electrical failure was not observed, but resistances started to decrease (without ever dropping below 1,000 Ω) between 1114 and 1130 seconds. The highest cable thermocouple temperature at that time was approximately 339 °C.

The remaining PSHV tests were both performed at a shroud temperature of 455 °C and the results provide some indication of the repeatability of the Penlight tests. Temperature and resistance data obtained in these two tests are shown in Figs. 4 and 5, respectively. In the third PSHV test electrical failure was first observed between Conductor 2 and Ground. In the fourth test electrical failure was first recorded between Conductor 1 and Ground. The highest cable thermocouple temperature at the time of electrical failure was approximately 386 °C and 358 °C in the third and fourth test, respectively.

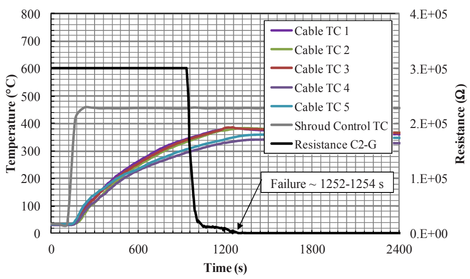

Fig. 4. Temperature and electrical resistance data obtained in the third PSHV test.

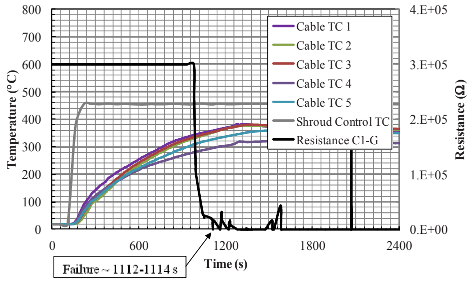

Fig. 5. Temperature and electrical resistance data obtained in the fourth PSHV test.

3. THIEF model calculations

3.1. THIEF model

Andersson and Van Hees proposed that the thermally-induced electrical failure (THIEF) of PVC insulated cables can be predicted via a simple one-dimensional heat transfer calculation, under the assumption that the cable can be treated as a homogenous cylinder [4]. McGrattan used the Penlight data from the CAROLFIRE program to extend the validity of the THIEF model to a wide range of cable types. A brief description of the THIEF model based on McGrattan's discussion in Reference [3] follows.

The simplifying assumptions underlying the model are as follows:

1. The heat penetration into a cable of circular cross section is largely in the radial direction.
2. The cable is homogenous in composition.
3. The thermal properties – conductivity, specific heat, and density – of the assumed homogenous cable are independent of temperature.
4. It is assumed that no decomposition reactions occur within the cable during its heating, and ignition and burning are not considered in the model.
5. Electrical failure occurs when the temperature just inside the cable jacket reaches an experimentally determined value.

Given these assumptions, the governing equation for the cable temperature, $T(r,t)$, is given by:

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) \tag{2}$$

where ρ, c, and k are the effective density, specific heat, and conductivity of the solid, all assumed constant. The boundary condition at the exterior boundary, $r = R$, is given by:

$$k\frac{\partial T}{\partial r}(R,t) = \dot{q}''_{net} \tag{3}$$

where $\dot{q}''_{net}$ is the assumed axially-symmetric net heat flux at the exterior surface of the cable.

The THIEF model employs a single value for the specific heat and the thermal conductivity, 1.5 kJ/kg·K and 0.2 W/m/K, respectively, for both thermoset and thermoplastic cables. The emissivity of the cable jacket is assumed to be 0.95. These property values are typical of several types of commonly used cable jacket and insulation materials [5]. The bulk density of the cable, ρ, can be calculated by dividing the mass per unit length by the cross sectional area.

3.2. THIEF model calculations for tests in which electrical failure was observed

Figures 6-9 compare the THIEF model predictions to the temperature measured under the jacket for the Penlight tests in which electrical failure was observed. The agreement is quite remarkable, given the simplicity of the THIEF model. For the final CCV test, the net heat flux in Equation (3) was determined based on Equation (1), with the exterior surface temperature of the cable replacing the gauge temperature and an emissivity of the cable of 0.95 instead of 1 for the gauge. However, in the final CCV test the cable specimens ignited and there was extensive melting and dripping. As a result, the interior of the Penlight shroud had to be cleaned and in the process part of the paint was inadvertently removed. It is assumed that this adversely affected the heat transfer characteristics of the shroud surface. Consequently, the THIEF calculations for the PSHV tests were performed with $\varepsilon_s = 0.82$ and $h = 0.005$ kW/m^2·K. Additional heat flux calibrations are needed to confirm these values.

3.3. THIEF model calculations for tests in which electrical failure was not observed

Figure 10 shows an example of a Penlight test in which electrical failure was not observed. Except for the first six minutes of Penlight exposure, the THIEF model significantly overpredicts the temperature under the jacket. In this case the model actually predicts cable failure while this was not observed in the test. Hence, the THIEF model errs on the conservative side. A possible explanation for the discrepancy is that the THIEF model does not account for heat losses along the conductors (see assumption #1).

4. Conclusions

Two types of eight-conductor cables that are used in nuclear plants in Japan were tested in the Penlight apparatus at SwRI. The first cable, referred to as CCV, has cross-linked polyethylene (XLPE) insulation and a heat resistant vinyl (PVC) jacket. The second cable, referred to as PSHV, has fire retardant ethylene propylene rubber (EPR) insulation and a fire retardant low hydrochloric heat resistant vinyl (PVC) jacket. The CCV cable temperature under the jacket at the time of electrical failure was 402 ± 20 °C. The PSHV cable temperature under the jacket at the time of electrical failure was 371 ± 14 °C. For both types of cables and the tests in which electrical failure was observed, the THIEF model predicts the temperature under the jacket with remarkable accuracy. However, the THIEF model overestimates the cable temperature at the end of the tests in which failure was not observed. A possible explanation for this discrepancy is that the model does not account for heat losses along the conductors. The intent is to perform Penlight tests on six other types of cables and to extend the validity of the THIEF model to a wider range of cables used in nuclear plants in Japan.

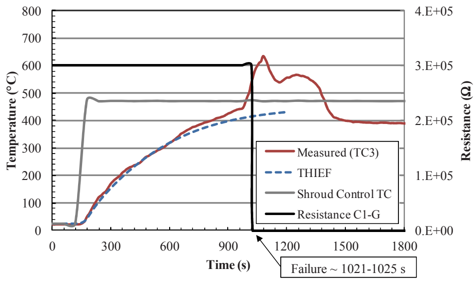

Fig. 6. THIEF model predictions and selected measurements obtained in the final CCV test.

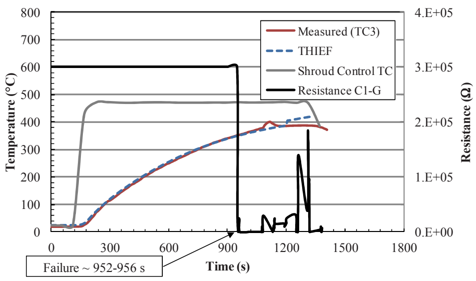

Fig. 7. THIEF model predictions and selected measurements obtained in the first PSHV test.

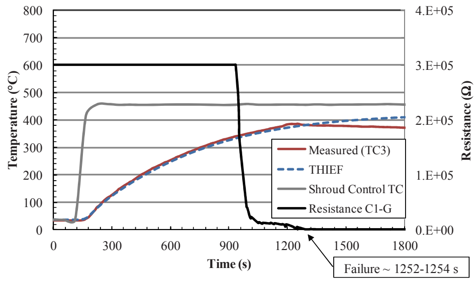

Fig. 8. THIEF model predictions and selected measurements obtained in the third PSHV test.

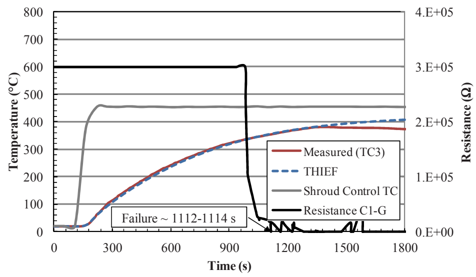

Fig. 9. THIEF model predictions and selected measurements obtained in the fourth PSHV test.

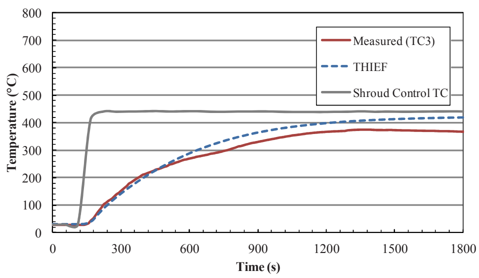

Fig. 10. Temperature and electrical resistance data obtained in the third CCV test following the preliminary test.

Acknowledgements

The support by the Japan Nuclear Energy Safety Organization for the work described in this paper is acknowledged and greatly appreciated.

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